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Abstract

Electrical Resistance Tomography (ERT) installed to track the development of an injected subsurface CO_2 plume at the SECARB Cranfield, MS. sequestration site will be the deepest subsurface application of this method to date. ERT utilizes vertical arrays of electrodes, usually in a cross-well arrangement, to perform four-electrode measurements of changes in the spatial distribution of electrical resistance within a subsurface formation. Because a formation containing super-critical CO_2 is approximately five times as resistive as its surroundings, significant resistance changes are anticipated during plume growth and movement within a brine-filled formation. ERT has also been shown to be quite sensitive to CO_2 saturation changes. The Cranfield ERT electrode arrays will be emplaced at a depth exceeding 10,000 ft. (3280 m); the system design and installation must address significant challenges associated with both the depth and borehole conditions including temperatures of 258 F (126 C), pressures exceeding 5000 psi and a groundwater pH of 3. In addition, the system must allow co-located emplacement and concurrent operation with other monitoring techniques that utilize the same boreholes. ERT electrode and cabling will be attached to the outside of the well casing, allowing free access to the interior of the well, which is required by some of the other monitoring techniques being fielded. We will highlight these design challenges along with preliminary simulations indicating the anticipated level of imaging and the advantages of applying the technique in conjunction with other methods (such as cross-well seismics) to more accurately track the properties, location and movement of CO_2 plumes.

Introduction

Tracking Subsurface CO_2 Injection With Changes In Electrical Properties

Sequestration of CO_2 in geologic formations will require ongoing observations of the subsurface reservoirs to assess the overall level of CO_2 containment, the nature of leakage paths and to better understand how the injected CO_2 might interact with its storage environment. Future sequestration reservoirs will be at depths of thousands of feet to miles and may be characterized by temperatures and pressures in the range of hundreds of degrees and thousands of psi. Because deep observation wells penetrating a prospective sequestration reservoir are so expensive to drill, it is also apparent that multiple observation techniques will likely be required to share a well to gain access to the reservoir environment. Thus, robust remote observation methods are required that produce minimal interference with other methods operating in the same well.

Electrical imaging techniques are well-suited to monitor changes resulting from injection of fluids because the electrical properties of a formation are often dominated by the electrical properties of the fluids within them, and the techniques are particularly sensitive to changes in the fluid properties. Super-critical CO_2, the fluid has physical and chemical properties that are significantly different from the fluids it displaces (e.g., oil and water). For example, the electrical resistivity contrast as observed in the Maljamar super-critical CO_2 flood test performed in Lea County, NM was readily detectable. Induction logs of formations flooded with CO_2 showed formation electrical resistivity increases of five times the pre-flood values (Ref. 1) that were almost certainly produced by CO_2 saturations much less than 100%. High resolution mapping of subsurface electrical properties has been successfully performed in hydrologic systems having much smaller resistivity contrasts for the purpose of site characterization and for monitoring fluid migration in the subsurface (Ref. 2). Based on such considerations, electrical methods appear to be highly appropriate for tracking changes in the subsurface caused by the growth and movement of injected super-critical CO_2.

Application Of Geophysical ERT

Electric resistance tomography (ERT) is an electrical measurement technique that can be used to measure the subsurface distribution of electrical resistivity from a large number of resistance measurements made using electrodes positioned within a volume surrounding the region of interest. Unlike induction logging, which obtains the resistivity distribution of a formation by electromagnetically inducing detectable currents within the formation, application of the ERT method is based upon an **Ohm's law** relationship involving the injected current between any two of the electrodes, the formation resistivity and the voltages measured at the remaining electrodes. The method is mechanically robust because the field system components that are emplaced in the subsurface consist primarily of metal electrodes and cabling that attaches them to a surface current source and voltage-data acquisition system. The electrodes and cabling can be mounted on the outside of non-conductive well casing (e.g., fiberglass reinforced pipe or FRP) forming a vertical electrode array. The casing is then lowered and grouted into the borehole in typical oil-field fashion. Because all the ERT cabling and electrodes are buried in the cement on the outside of the well casing, application of the ERT method need not interfere with subsurface observation techniques that operate on the inside of the well casing. Importantly, this differs from wireline induction logging, which entails lowering a combination electromagnetic receiver-transmitter tool along the length of an open well: a requirement that is generally not possible to meet when a well must be simultaneously shared with other observation methods that remain installed within the casing.

[Figure 1]

Once subsurface ERT electrode arrays are installed in a geometrical pattern, such as the cross-well arrangement designed for the SECARB Cranfield observation wells illustrated in Figure 1, initial testing of the system is performed followed by obtaining a baseline resistivity distribution of the subsurface volume probed by the electrical current flowing between the electrodes. The baseline resistivity distribution is important because the detection of flow-induced changes in a particular formation resistivity distribution is accomplished by subtracting "before" and "after" snapshots of the distribution in a manner similar to time-lapse seismic.

The electrical data required to calculate the resistivity distribution is obtained by making a series of four-electrode measurements. The four-electrode approach minimizes the effect of contact resistance and polarization at the interface between the electrodes and the soil matrix/pore-fluid regime. A given current is injected between two electrodes and the potential difference is measured between two other electrodes in the arrays. [Note: Most generally, the transmitted AC current of frequency ω, that is, $\mathbf{I}(\omega)$ is related to the voltage $\mathbf{V}(\omega)$ by Ohm's Law,

$$\mathbf{V}(\omega) = \mathbf{I}(\omega)\ \mathbf{Z}(\omega)$$

where $\mathbf{Z}(\omega)$ is the complex impedance. These quantities are complex to account for both the magnitude which gives ohmic resistance and the phase yielding induced polarization information. (See Ref. 3)] To build up an adequate data set of voltages that can be used to invert for the subsurface resistivity distribution, the measurement process should include all possible measurement combinations of current injection electrodes and voltage that are linearly independent. For a total of **n** electrodes in an ERT system (e.g., the Cranfield cross-well system involving one vertical array of 14 electrodes and another of 7 electrodes has $\mathbf{n = 21}$), there are $\mathbf{n(n-3)/2}$ (or 189) linearly independent combinations for the Cranfield ERT system. It is also important to sample the array to obtain reciprocal measurements. A reciprocal measurement is made by exchanging the two current injection electrodes with the two voltage measurement electrodes in a 4-electrode measurement. If the relationship between the arrays and the formation resistivity follows the linear Ohm's law, measurements and their reciprocal should yield the same transfer impedance. Differences in the transfer impedances calculated from a measurement and its reciprocal provide an estimate of the error.

[Figure 2]

Figure 2 is a schematic of a typical ERT data acquisition system. The basic components of the system are a transmitter or current source; receiver which measures the resulting electrode potentials; multiplexer for quickly and automatically connecting the electrodes to both the transmitter and receiver; and a computer for controlling the system and recording the data supplied by the receiver. The rate of data collection is affected by a number of factors, some being readily controllable while others are not. To reduce the interfering effects of electromagnetic induction in the very long (2 mile) cables used at Cranfield, square-wave current injection frequencies will be much less than 1 Hz. It is expected that a full suite of measurements at Cranfield will require several hours to obtain including the additional measurements required to perform waveform stacking to enhance the signal-to-noise ratio. Assuming formation resistivity in the range of about 1 ohm-m at Cranfield, we anticipate that our measured electrode potentials will fall between tens to hundreds of millivolts for the injection of one-amp currents.

Obtaining Resistivity Images From Geophysical ERT Data

Given a data set containing hundreds of voltage measurements at different spatial locations, construction of an acceptable model of the resistivity distribution responsible for the observed distribution of voltages is necessary. We use an inversion procedure that produces a solution giving an objectively acceptable fit to the data and also satisfies any other constraints that are identified. Owing to the rather finite number of spatial measurements of voltage comprising any ERT data set, any inversion yielding the distribution of electrical resistivity is necessarily under determined giving rise to an infinite number of potentially acceptable solutions. We can limit consideration to only those solutions that exhibit some anticipated characteristic such as maximal smoothness, which seems a reasonable assumption for a CO_2 plume. We can also specify that the solution smoothness is anisotropic, smaller along the vertical, as might be expected for plume flow moving along different more or less horizontal adjacent geo-hydrologic layers. Further details of the solution procedure involving inversion, forward modeling and objective functions are presented in references 3 and 4.

[Figure 3]

Figure 3 illustrates a resistivity solution obtained for two simulated lower resolution ERT data acquisition cross-well experiments (cross-well ERT with arrays of 7 and 14 electrodes). The target area consists of an anomalously resistive block with a thickness comparable to the Lower Tuscaloosa injection target layer at Cranfield and creating a resistivity contrast comparable to the Maljamar case. This is a very basic simulation of a hypothetical CO_2 injection creating a plume that partially fills a target region between two vertical electrode arrays spaced approximately 30 meters or 100 feet apart. The presence of the plume between the wells is readily detectable, although subsequent simulations suggest that any finer scale structure of the plume with the electrical properties assumed here will be more difficult to detect in the absence of much higher electrode spatial resolution. The ERT method as applied to the cross-well case is most sensitive to changes in the resistivity nearer the wells and is least sensitive in the region at the middle.

The DOE SECARB Cranfield ERT Experiment

The LLNL ERT system will be installed as part of the SECARB Phase III carbon sequestration program, which has the objective of demonstrating the long-term injection and subsurface storage of CO_2 in a deep saline reservoir near Cranfield, Mississippi. The project is intended to develop the technical background necessary for validating and deploying carbon sequestration technologies in the Southeastern US. Phase III work represents the first attempt to design, install and operate an ERT system at a depth of approximately two miles or about 3200 meters. Previously, most ERT data acquisition has been performed in wells that are less than 100 meters deep having been motivated by tracking groundwater flows, monitoring steam injection during contaminant cleanup efforts, and vadose zone imaging. However, LLNL has successfully performed ERT imaging at a depth of more than 1200 feet or 375 meters to monitor steam flooding in a Central California oil field (Ref. 5). Recently, researchers in Ketzin, Germany have installed an ERT system reaching a depth of about 700 meters and have reported some initial results that are promising (Ref. 6). They inserted the ERT system mounted on the outside of well casing through an over-bored and cased hole that provided partial protection for the electrode arrays during the emplacement process. Their electrode spacing of 10 meters or about 30 feet is comparable to one of the cross-well arrays planned for Cranfield, but has a spacing that is double that of the other Cranfield observation well. They also have installed a third electrode array in a well that is not co-linear with the others so that 3D observations can in principle be obtained.

[Figure 4]

The Cranfield CO_2 sequestration site is in Adams and Franklin Counties, approximately 12 miles east of Natchez, Mississippi. The underlying gas cap of the Basal Tuscaloosa reservoir was discovered in 1943 by Chevron Oil during drilling to a depth of over 10,000 feet (3200 meters). A productive area of eventually almost 8000 acres has been defined by nearly 100 producing wells and only a few dry wells. Figure 4 is a cartoon illustration the approximate Phase III target zone for injection and observation of the CO_2 plume in the Lower Tuscaloosa sands. The sands are interbedded with shale and the total thickness of the injection or observation layer is expected to be about 60 to 80 feet (20-25 meters).

In the Phase III activities involving ERT observations, three wells will be drilled to depths of over 10,000 feet terminating below the target zone. The wells, drilled collinearly, will be perforated in the target zone. The first well to be drilled is an injection well while the other two are observation wells. The injection well will be located just down dip from the observation wells at a distance of about 40 meters from the first observation well. The second observation well is spaced 100 feet (~ 30 meters) from the first observation well. It is expected that pressure drive associated with injecting the CO_2 will be primarily responsible for moving the plume into the target zone between the two observation wells.

Challenges Of The Cranfield ERT Application

Several challenges arising from this particular application must be considered in the ERT system design and operation. The first and most obvious is that the Phase III effort will involve an attempt to install an operable system in the deepest observation wells that have ever been accessible to ERT experiments since the development of the technique. Besides requiring very long runs of cable (over 2 miles) that have the potential to introduce new operational challenges, the ERT system will terminate in a target zone having temperatures in excess of 120 C (250 F) and highly acidic ground water (pH ~3). While ERT system components (electrodes and cabling) tend to be rather rugged compared to other types of sensors, (e.g., seismic, pressure gauge) the system must still be designed to take into account the deleterious effects of temperature and ground water chemistry if long-term operation is required. Another challenge specific to the Cranfield application is that the ERT system must be mounted external to the well casing and be subjected to a very long run in an open hole. While ERT systems are conventionally mounted on the outside of a plastic (pvc), non-conductive casing, the insertion depths have been very much shallower in previous installations. Because of the very long runs of exposed borehole wall in the Cranfield case, a higher probability exists that non-uniformities in the open-borehole wall will catch or snag the cabling system as it is lowered down the well. Furthermore, if the hole is not straight during the casing insertion, which is not unusual for a 2-mile deep well, the weight of the casing can potentially ride on the cabling causing abrasion or even breakage if enough centralizers are not used. In a very long, open borehole, another concern is that falling debris breaking off anywhere from the borehole wall can grind against the cabling and connectors on their downward trip causing damage if they are not sufficiently armored. The Cranfield ERT system has been designed to minimize the potential for deployment failure, making use of centralizers and cable protection (described below). Once the system reaches the bottom of the borehole, the well is grouted in. This involves pumping cement down the well and up the annulus formed by the casing and borehole wall. This activity represents yet another possibility for abrasion of the exterior-mounted cabling and components to occur.

Once the two observation wells are completed, they will host a variety of observation techniques and it is likely that some the techniques will interfere with each other. Table 1 lists *some* key Phase III observation and analysis techniques that will be employed in the wells. For example, the ERT system will not be installed in the hole alone on the outside of the well as the Distributed Temperature Sensing (DTS) system will also be conveyed on the outside of the casing along with a pressure sensor. Both the ERT and DTS systems involve electric currents that could potentially induce signals in each other’s data acquisition system as well as those of some of the other techniques. To eliminate inductive effects as much as possible we anticipate using very low sampling frequencies (< 1Hz) during the operation of the ERT system. Another potential challenge is that near-well, thermal perturbations resulting from the operation of the DTS system will modify the background-resistivity field sufficiently that baseline ERT observations will be required at the times of maximum and minimum temperature perturbations.

Table 1
Key Phase III Well-Based Observation And Analysis Techniques

Measurement Technique	Motivation	Application
Electric Resistance Tomography	Improve estimation of CO_2 saturation, injected plume volumes, locations	Tool development will extend range of cross-well measurement of saturation and improve joint inversions involving other data
Continuous Active Source Seismic Monitoring (CASSIM); cross-well seismic tomography	Detect timing of plume movement across plane of measurement	History match model involving high frequency temporal records and pressure signal; improve joint inversions
Distributed Temperature Sensing (DTS)	Measure zones of fluid movement	Additional data to constrain flow-unit thicknesses; correlate with other methods
Produced Fluid Composition (U-Tube Sampler)	CO_2 via mass, DIC, DOC; Selected major and minor cations, organics	Validation of well log and cross-well CO_2 detection, indicator of rock-water reaction.
Bottom-Hole Pressure	Tracking multiphase flow and effect of injection on local pressure field	Assess relationship between pressure and multiphase flow

[Figure 5]

An additional possibility for interference involves the fluid sampling that will occur within the cased well. For formation fluids to be sampled, perforation of the electrically insulating well casing is necessary. However, electric currents injected during ERT observations now have access to the interior of the well through the perforations. Figure 5 illustrates how currents can stray into the well casing and be channeled along any bare metal components that are present. We estimate that 3% of injected current could be lost to the inside of the well as a result of flow along long runs of bare metal tubing and pipes in the well. To avoid this, all long runs of metal will be insulated before or during the final installation.

Engineering The Cranfield ERT System

In collaboration with engineers at Promore Engineering and Sandia Technologies, both in Houston, TX, we are working to develop a robust ERT system that can be casing-conveyed and operate at the depths and under the conditions required for this project. In designing this system we have sought to achieve several different and sometimes conflicting goals. One is design and construct an exceedingly rugged system that can survive emplacement in a very deep borehole under extreme temperature, pressure and chemical conditions. Another is to design a system that can still be functional even if the installation process does not go as planned or a sealing component failure occurs. Once the ERT system is installed, it cannot be removed again for repair. Given the high cost of rig time, the system needs to be designed and built to be readily assembled and attached to the casing as it is prepared to go into the borehole.

[Figure 6]

The Cranfield ERT system uses custom built wireline cabling that has a woven dual armored steel-stranded covering encasing seven Teflon insulated #16 AWG conductors (Fig. 6). Observation well #1 (closest to the injector well) will be fitted with 14 electrodes and therefore requires two such cables that run along the outside of the approximately 10,000 feet of steel well casing before transitioning to non-conductive fiberglass reinforced pipe (FRP).

[Figure 7]

To further protect the dual armored cabling, centralizers and cable protectors will be employed (Fig. 7) that span every casing joint with an armored gallery containing the wireline cables. The intent of the galleries is to prevent pinching of the cables at points where the thicker casing joints reduce the clearance with the borehole wall.

[Figure 8]

The dual armored cable (DAC) run is terminated at the downhole end of the ~10,000 feet of steel casing into a specially designed and built, high pressure and temperature bulkhead connector. Figure 8 illustrates a connector similar to the custom connector/splitter developed for the Cranfield system. The connector splits the DAC into 7 separate encapsulated conductors. In Observation well #1 two such splitters will be required yielding 14 conductors at the point of transition to the FRP.

[Figure 9]

Roughly 400 ft of FRP attached to the down hole end of the steel casing will be emplaced in the well so that it is approximately centered on the target zone of injection. Each of the conductors split out from the DAC will transition to an insulated, tube encapsulated conductor (TEC) that is intended to prevent abrasion of the Teflon electrical insulation during installation and keep it dry (Fig. 9). An added filler separates the insulated wire from the stainless tubing to minimize the possibility of cross talk between cables if the Teflon on a conductor becomes both damaged and wet. Furthermore, the general approach to separating the conductors is intended to prevent cross talk in the event of damage to two or more of the cables in an array.

[Figure 10]

Through a splicer, a tubing encapsulated conductor is terminated into each electrode as shown Figure 10. Centralizer ribs are molded into each length of FRP and are used to lock the position of the electrodes so that they cannot slide or twist when mounted on the FRP.

Once the ERT system has been conveyed to the bottom of the hole, the hole is grouted so that the electrode system ultimately becomes encased in cement. This is typical in ERT installations and is not an issue if the cement has a characteristic electrical resistivity that is similar to that of the formation. Perforation of the FRP in the target zone is necessary once the cement has set, which will be accomplished using a down hole orientation system, to ensure the perforations are created on the opposite side of the casing from the ERT cables.

After installation is complete, a series of tests will be performed and baseline resistivity images obtained with the ERT system. The initial tests will include checks for continuity and cross talk between the electrodes. We will also look for interference with other observation techniques. The outcome will determine the extent to which a data collection schedule that allows the different methods adequate sampling time to obtain data in a stand alone mode will be required. or if multiple methods can collect data at the same time.

Combining ERT With Other Types Of Data

Simulating A Joint Inversion Using Synthetic Data

An attractive aspect of observation wells hosting different CO_2 sensing techniques is the opportunity for combining the observations to obtain a more complete picture of the state of the plume. The Phase III activities will include cross-well seismic, temperature, DTS and fluid sampling in addition to ERT, and some preliminary idealized calculations, involving synthesized data sets, have been made to evaluate the effect of performing a joint inversion of disparate observation well data sets (Ref. 7). The synthetic data sets were constructed assuming a model of an injected CO_2 plume corresponding to a temporally growing elliptical-box volume with 40% saturation. As described next, the synthetic data were generated using accepted relationships between observables, such as temperature, electrical resistivity and seismic velocity, and the characteristic properties of the plume (saturation, size, CO_2 resistivity, etc.)

For tracking possible changes in the amount of CO_2 maintained in the reservoir, an important property of the plume is its saturation. One strength of ERT is its sensitivity to changes in a partially saturated regime such as will occur during injection during the Phase III activities. For a primarily sandy medium such as the Lower Tuscaloosa formation, we anticipate that Archie's equation will provide an acceptable functional relationship between the formation resistivity (ρ_r) and the water saturation (S_w):

$$\rho_r / (\rho_w \phi^{-m}) = S_w^{-n}$$

where ρ_w is water resistivity, ϕ is formation porosity and **m** and **n** are empirically derived constants. To estimate the effects of CO_2 on the formation resistivity, it is typically assumed that it is an insulator like air compared to the brine, that it does not dissolve in the oil phase and that it does not react with the rock/water system. To improve the estimates of saturation from the resistivity observations, one or two of these assumptions may ultimately require slight revision, particularly the assumption that the interaction of CO_2 with the rock/water system can be neglected. Otherwise, details of the approach to obtaining CO_2 volume estimates are relatively straight forward (Ref. 4).

Other assumptions used in synthesizing the data included a porosity of $\phi = 0.25$; that the temperature in the formation would decrease from 125 C to 124.8 C as the CO_2 saturation changes from 0 to 100%; that bulk pressure changes in the reservoir, relating to tilt measurements, are directly proportional to CO_2 saturation of the reservoir layer and that changes in the P-wave velocity detected by seismic tomography can be converted to CO_2 saturation using a petrophysical model such as a modified Gassman model. Additional discussion of the uncertainties and limitations of these assumptions is presented in Reference 7.

The joint inversion of the synthetic data was accomplished using an LLNL stochastic inversion approach that has been dubbed "The Stochastic Engine". The tool uses statistical theory and geophysical forward models to compute images of the subsurface plumes. It produces plume images that are consistent with disparate data types such as measurements of temperature, injected plume volume, ground deformation measurements and cross-borehole electrical resistivity and seismic measurements. The reconstruction method uses Bayesian inference, geophysical forward models and prior knowledge (e.g., flow meter measurements of the injected CO_2 volume and knowledge that the plume should connect to the injection well). The result is a sample of the posterior distribution containing the most likely plume models that are consistent with the data collected. The method uses a Markov Chain Monte Carlo (MCMC) technique to sample the space of possible plume models (i.e., the shape, plume location and CO_2 content of the plume).

Some Results Of Joint Inversions Involving Synthetic Data From Different Observation Techniques

[Figure 11]

The analysis of the synthetic data from the different observation techniques demonstrated that the best (most accurate) joint inversion results were obtained when two cross-well techniques (e.g., seismic and ERT) were deployed simultaneously in addition to temperature surveys and injected volume (Ref. 7). Two different plume sizes were considered corresponding to early and late times in the injection process. Figure 11 illustrates map and side views of the first and second most likely models of the late-time (larger) plume that best fit all the data sets. The black lines forming an ellipse in the map view and rectangular box in the side view correspond to the "true" size and shape of the plume in those views. The colored areas indicate the saturation which has a "true" value of 40%. Again, this figure corresponds to the later time when the plume is larger. It is not surprising that the best-fit solutions were in better agreement in the larger than in the smaller plume (not shown) cases.

[Figure 12]

The plume is not resolved as well when only one cross-well technique (ERT) is used as shown in Figure 12. In general it was found that more cross-well techniques provided a better fit to the 'true' plume properties and using single well temperature or tilt data alone produced the worst fit. The study outlined here clearly supports a joint inversion approach involving data from as many cross-well techniques as is available.

Conclusions

ERT as applied at Cranfield is a cross-well electrical resistivity imaging technique that shows significant promise for tracking CO_2 plume growth and movement. Because the ERT system components are cables and electrodes, it is robust and can be mounted on the outside of a well casing and then cemented in place. Furthermore, unlike induction logging, a casing-conveyed ERT system will not interfere mechanically with other CO_2 detection and observation methods that operate within the well casing. The opportunity to install the world's deepest cross-well ERT system during the Phase III operations at Cranfield is driving a significant development effort to produce a high reliability, low interference system that can provide useful input directly to decision makers and also input into future joint inversions of disparate data sources to improve the characterization of the injected plume.

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Figures

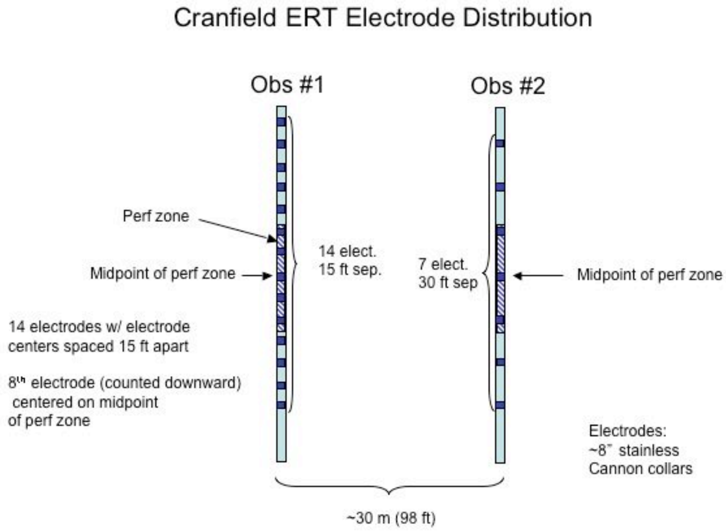


Figure 1.

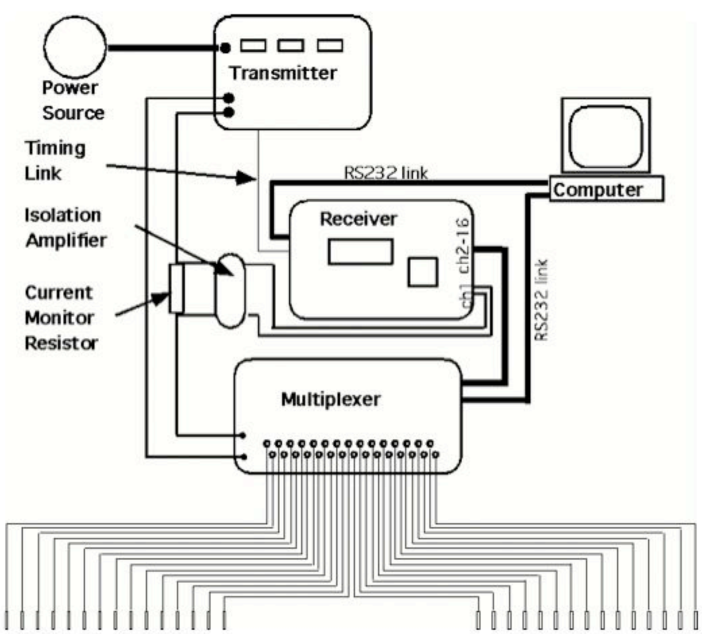
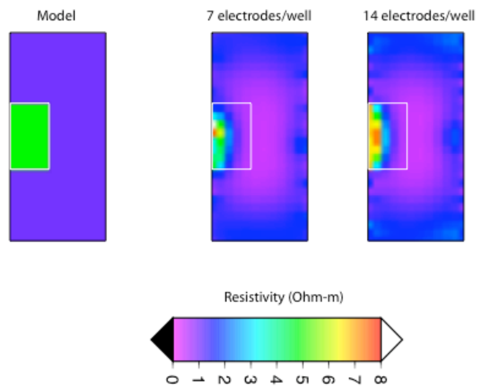


Figure 2.



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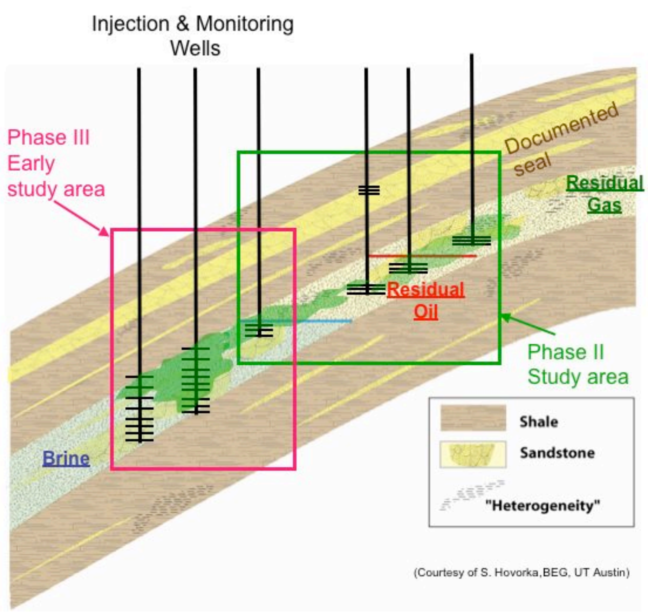


Figure 4

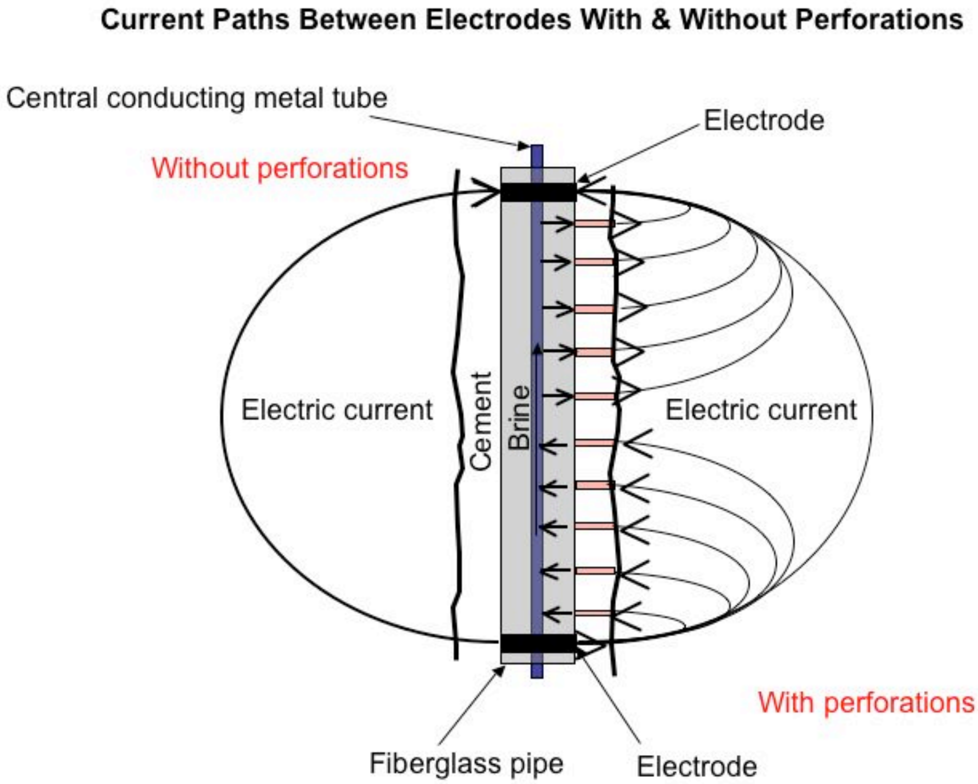
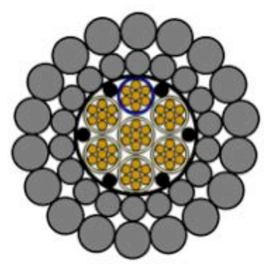


Figure 5

Manufacturer:	Rochester Cable Corp.
Conductors:	7 (16 AWG)
Insulation Type:	Teflon (FEP)
Armor Material:	Galvanized Carbon Steel
Overall Size:	0.420 inch OD
Temperature Rating:	400 Fahrenheit
Breaking Strength:	>18,000 lbf
Crush Resistance:	Up to 13,000 lbf



Cross Section

Figure 6

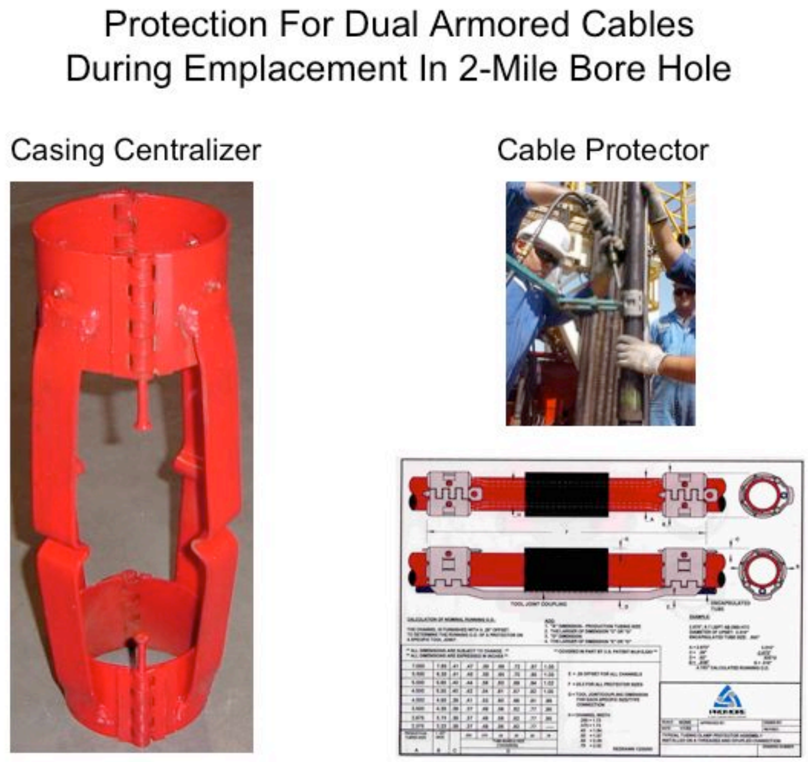


Figure 7

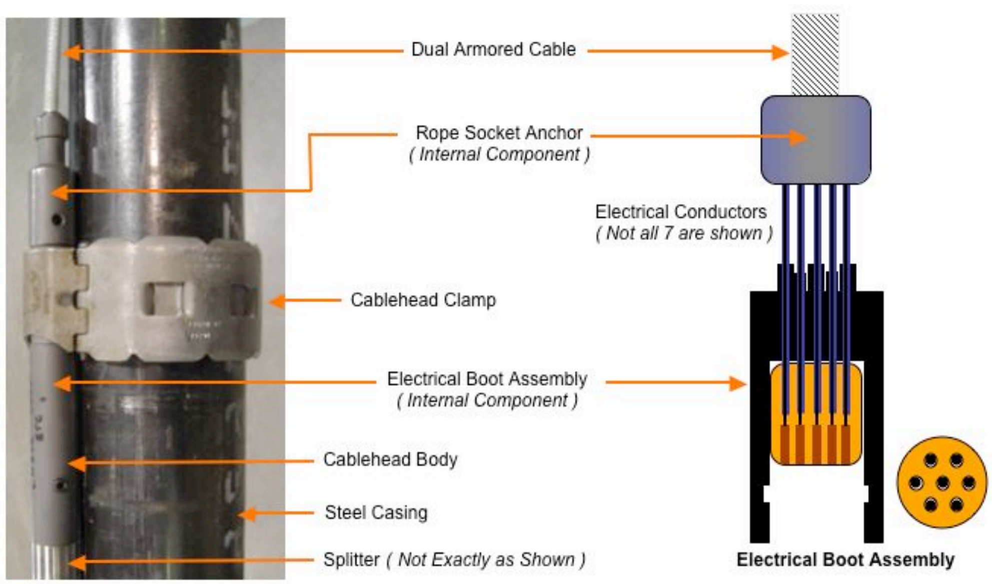


Figure 8

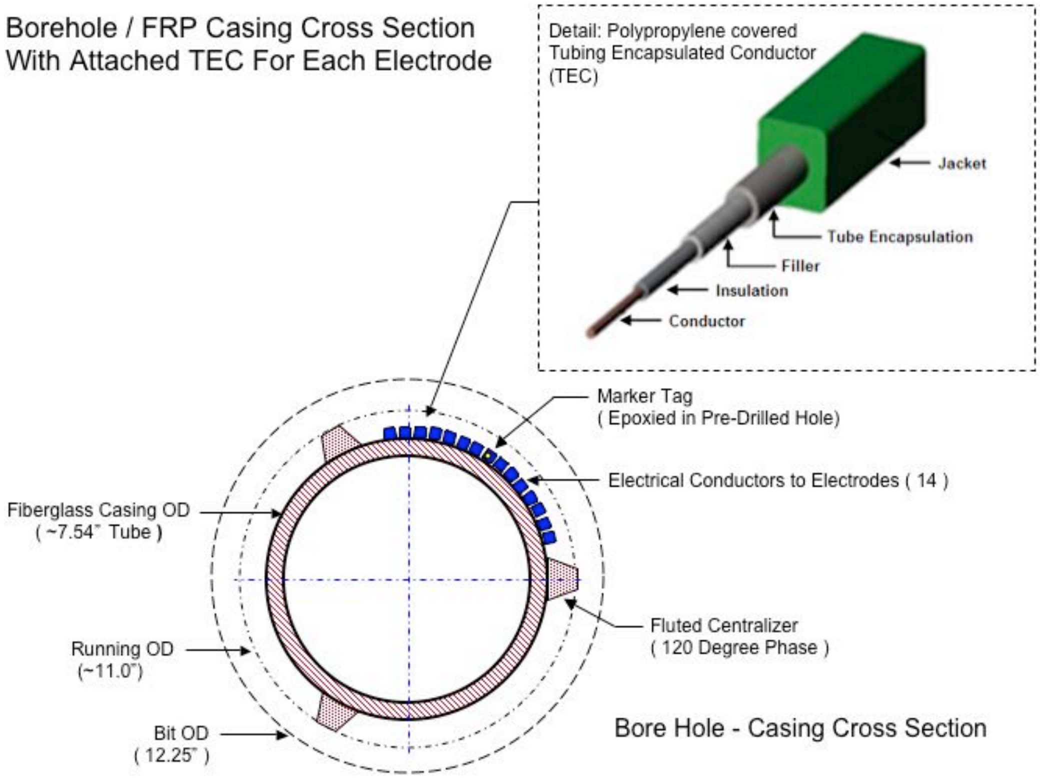


Figure 9

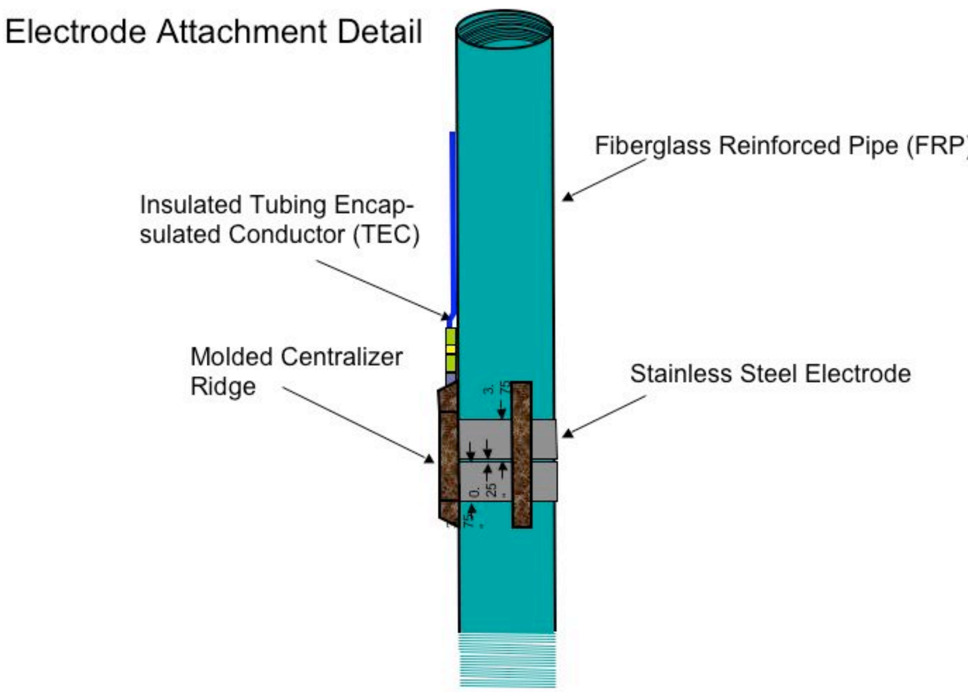


Figure 10

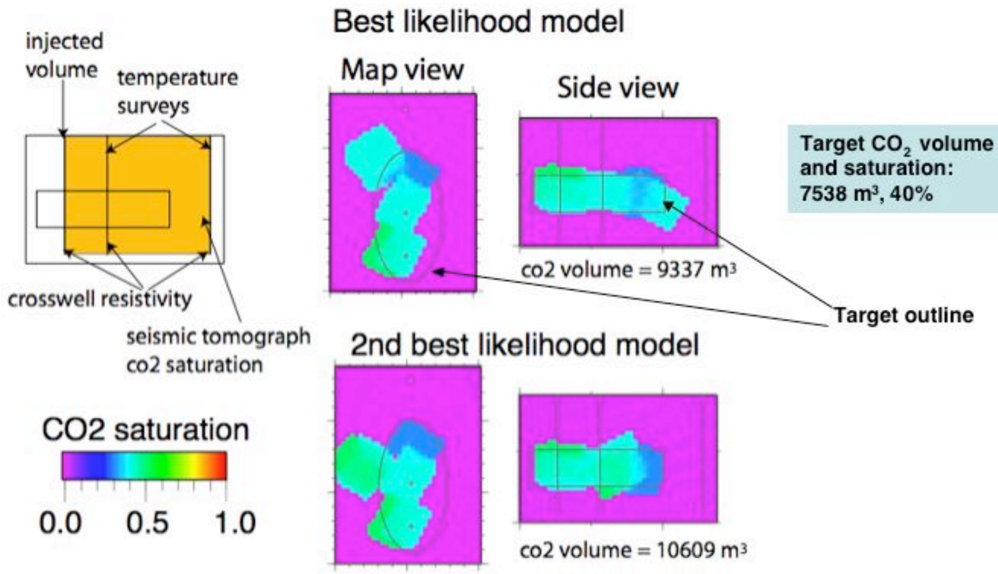


Figure 11

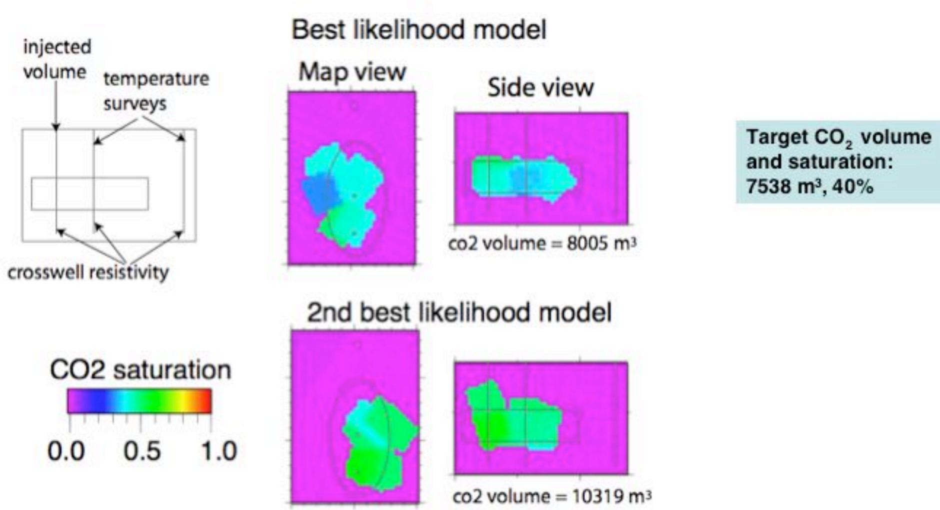


Figure 12